

BEAM DYNAMICS REQUIREMENTS FOR THE POWERING SCHEME OF THE HL-LHC TRIPLET*

M. Fitterer, R. De Maria, S. Fartoukh, M. Giovannozzi, CERN, Geneva, Switzerland

Abstract

For the HL-LHC, β^* values as small as 15 cm are envisaged as baseline scenario for the high luminosity insertions IR1 and IR5, thus leading to an increase of the maximum β -functions in the inner triplet (IT). The larger beta-functions in the IT result in a higher sensitivity of the beam to any linear or non-linear, static or dynamic, field imperfections in the IT region. In this paper, we summarize accordingly the tolerances of the triplet power supplies in terms of current ripple, stability and reproducibility. Both the baseline IT powering scheme and other alternative schemes will be presented, the later reducing the tune shift caused by a current modulation and thus weakening its possible impact on the long term stability.

INTRODUCTION

A modulation in the current of a power supply in general results in a change of the magnetic field which in turn causes a modulation of the normalized quadrupole strength. Possible effects of this modulation on the linear optics are β -beat, orbit deviations and a tune modulation, where the expected tune shift is given by the well known formula:

$$\Delta Q = \frac{1}{4\pi} \oint \beta(s) \Delta k(s) ds \quad (1)$$

with $\Delta k(s)$ being the modulation of the normalized quadrupole strength due to the modulation of the current by the power converter (PC) itself. As shown in [1] the β -beat and orbit deviation are small in case of the IT PCs in IR1 and IR5, while the effect on the tune is non-negligible. In addition, the modulation of the tune can also have an effect on the non-linear beam dynamics [2, 3] and has been experimentally demonstrated at several machines (e.g. at the SPS and HERA [4–7]), where the modulation resulted in a reduction of the beam life time and increased losses. In order to avoid a performance degradation due to the effect of a modulation of the PC current, an extensive beam dynamics study has been launched with the aim to specify the required tolerances. A short summary of this study is given in this paper.

MODEL OF THE IT POWER CONVERTERS

The first step in the specification of the tolerances of the IT PCs from a beam dynamics point of view, is to translate the voltage and current specification of the PC into a modulation

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of the normalized quadrupole strength. For the IT PCs two regimes are in general distinguished:

- **current-control:** for low frequencies (< 0.1 Hz) the current of the PC is directly controlled and the modulation of the quadrupole strength can be seen as random noise in the < 0.1 Hz range.
- **voltage-control:** due to the different components of a PC and the power grid itself, certain frequencies are present in the current spectrum, in general referred to as “ripple frequencies”. The tolerances for the different frequencies are usually given in terms of voltage.

As the magnetic field scales linearly with the current, the normalized quadrupole strength is given by:

$$k(f) = T_{\text{Itok}}(f) \times I_{\text{PC}}(f) \quad (2)$$

in case of a direct control of the current.

To translate the voltage modulation in a modulation of the normalized quadrupole strength, the following model has been applied:

$$k(f) = T_{\text{Itok}}(f) \times T_{V_{\text{toI,load}}}(f) \times V_{\text{PC}}(f) \quad (3)$$

where T_{Itok} is the transfer function from the PC current to the normalized quadrupole strength, which is assumed to be constant, $T_{V_{\text{toI,load}}}(f)$ is the transfer function of the circuit seen by the PC and $V_{\text{PC}}(f)$ is the voltage modulation. The circuit of the super-conducting IT magnets seen by the PC ($T_{V_{\text{toI,load}}}(f)$) can in general be represented by an RL circuit. This implies that the higher the magnet inductance of the circuit, the stronger the attenuation of the modulation of the current and thus normalized quadrupole strength. In this model the effect of the cold bore, absorbers and beam screen is not included due to which an additional frequency dependent attenuation is expected.

IT POWERING SCHEMES

For the HL-LHC IT three different powering schemes are considered at the moment, which are illustrated in Fig. 1. The scheme “Baseline” is the current baseline powering scheme [8, 9], and the schemes “Q1Q2Q3” and “Q1Q2a-Q2bQ3” are alternative powering schemes under consideration. As will be shown later, the scheme Q1Q2a-Q2bQ3 features the smallest tune shift in the current-control regime and the scheme Q1Q2Q3 in the voltage-control regime due to its large inductance ($L_{\text{tot}} = L_{Q1} + L_{Q2} + L_{Q3}$). The magnet inductance and resistance used for the calculation of the normalized quadrupole strength with Eqn. 3 are summarized in Table 1.

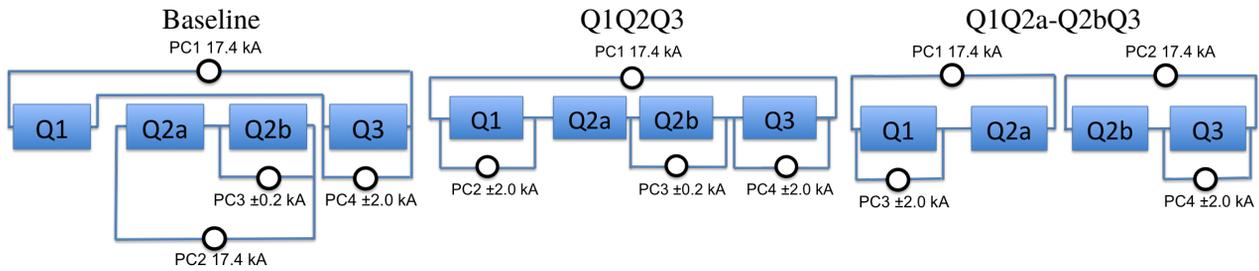


Figure 1: Powering schemes for HL-LHC IT.

Table 1: Magnet Inductance and Resistance for the IT Magnets. For the calculation of the normalized quadrupole strength, the values for the layout version HLLHCV1.0 have been used. Both Q1 and Q3 consist of two 4.0 m length magnets which are in series and thus a length of 2×4 m has been used for the calculation of the inductance.

	length [m]	\mathcal{L} [mH/m]	L [mH]	R [m Ω]
Q1/Q3	2×4.0	10.8	86.4	1.144
Q2a/Q2b	6.8		73.44	

SIMULATION RESULTS FOR THE CURRENT-CONTROL REGIME

From a beam dynamics point of view, the most relevant figure of merit is the tune variation induced by the modulation of the normalized quadrupole strength of the IT [1]. In the current-control regime, the modulation of the normalized quadrupole strength is random (with low frequency). Thus to obtain the tune shift in this regime, Monte Carlo (MC) simulations with 10 000 seeds have been conducted for the layout version HLLHCV1.0 and squeezed optics with $\beta^* = 0.15$ m assuming a uniformly distributed relative current error of

$$\frac{\Delta I}{I_{\max,PC}} = 10^{-6}$$

peak to peak where $I_{\max,PC}$ is the maximum current of the PC, yielding the results summarized in Table 2.

Table 2: RMS Tune Shift Assuming a Uniformly Distributed Current Error of $\frac{\Delta I}{I_{\max,PC}} = 10^{-6}$ Peak to Peak. z stands for the x - or y -plane respectively.

	$\text{rms}(Q_z - Q_{z0}) [10^{-4}]$	$\Delta Q/\Delta Q_{\text{Base}}$
Baseline (Base)	1.36	1.0
Q1Q2Q3	0.67	0.5
Q1Q2a-Q2bQ3	0.54	0.4

The Q1Q2a-Q2bQ3 scheme has been proposed as the option featuring the lowest rms tune modulation which is confirmed by the MC simulations. For all squeezed optics the results can be simply scaled with the β^* :

$$\Delta Q_z \sim \left(\frac{1}{\beta_z^*} \right), \quad z = x, y \quad (4)$$

where β_z^* is the β -function at the IP in the transverse plane.

SIMULATION RESULTS FOR THE VOLTAGE-CONTROL REGIME

In the voltage-control regime only certain frequencies are present and they are known as power supply ripple frequencies. These ripple frequencies introduce additional resonance side bands [2, 4]:

$$lQ_x + mQ_y + n \frac{f_{\text{mod}}}{f_{\text{rev}}} = r, \quad \text{with } l, m, n, r \text{ integer} \quad (5)$$

To study the effect of the resonance side bands, dynamic aperture (DA) studies have been performed and the simulation results analysed applying two different criteria:

- **Particle lost criterion:** the DA is defined by the amplitude of the last stable particle, where the particle is considered unstable, when it is lost during the tracking over a maximum number of turns.
- **DA versus turns:** following the approach taken in [10] a more regular pattern can be obtained from the survival plots by averaging over the angles. The dynamic aperture is then defined as a function of the number of turns:

$$D(N) = \left(\int_0^{\pi/2} [r(\theta; N)]^4 \sin(2\theta) d\theta \right)^{\frac{1}{4}} \quad (6)$$

The “DA versus turns” criterion has been chosen in addition to the standard method – the “particle lost criterion” –, as it is a more suited criterion for detecting slow losses (see [3] for further details).

In order to ultimately determine the tolerances for the ripple frequencies of the PC, two kind of studies have been conducted for different scenarios:

- **determination of the dangerous frequencies:** The effect of a single frequency is studied by assuming the same modulation amplitude (normalized quadrupole strength) for all IT quadrupoles taking the magnet polarity and the powering scheme into account. The amplitude is chosen in order to obtain the desired tune shift, here

$$\Delta Q = \pm 10^{-3}, \pm 10^{-4}, \pm 10^{-5}, \pm 10^{-6}$$

The frequencies studied are those with higher expected voltage noise amplitude (Table 3), explicitly 50 Hz,

100 Hz, 300 Hz, 600 Hz and 20 kHz. 40 kHz and 10 MHz have not been studied as at such high frequencies the modulation amplitude is already heavily attenuated due to the high magnet inductance.

- **real frequency spectrum:** The effect of the real frequency spectrum is studied, where the frequency spectrum is given by the frequencies explicitly stated in the voltage spectrum (Table 3) and all 50 Hz harmonics up to 1 kHz. The voltage spectrum is then translated in a modulation of the quadrupole strength using Eqn. 3 taking the powering scheme, magnet inductance and magnet polarity into account.

These two kind of studies have been performed for the scenario with the maximum tune shift – at collision and including beam-beam effects with crab-crossing – as the decrease in DA due to the tune modulation is expected to be most sensitive in this case. All DA simulations have been conducted with SixTrack [11] for the sLHCv3.1b layout version [12],

Table 3: Expected Voltage Spectrum for IT PCs [13, 14]

frequency	Voltage [mV]
50 Hz	3.2
100 Hz	0.8
300 Hz, 20 kHz	10.0
600 Hz, 40 kHz	2.5
10 MHz	1.0
all others	0.5

round collision optics ($\beta^* = 0.15$ m), a normalized emittance of $3.75 \mu\text{m}$, 2.2×10^{11} particles per bunch and a maximum number of turns of 10^6 . For a detailed list of all simulation parameters it is referred to [1].

The results of the DA simulations can be expressed as tolerances in terms of tune shift and are illustrated in Fig. 2. The orange bars are the tolerances obtained from the “determination of the dangerous frequencies”, where for the smaller tune shift indicated by the orange bar no decrease of the DA in respect of the reference case without ripple is observed. The larger tune shift indicated by the orange bar is the smallest tune shift studied for which a decrease of the DA in respect of the reference case without ripple is visible. This means, that the real limit must thus lie within the orange bar. A clear sensitivity to 300 Hz and 600 Hz is visible. The different lines indicate the maximum tune shift for the different frequencies using the “real frequency spectrum” and the different powering schemes. The powering scheme “SixTrack slhcv31b” is the scheme used for the DA studies. This scheme has the same layout as the Baseline powering scheme, but using the single magnet inductance of Q1/Q3 and Q2a/Q2b as total circuit inductance instead of $L_{Q1} + L_{Q3}$ and $L_{Q2a} + L_{Q2b}$ respectively. Furthermore also the previous value of 10.8 mH has been assumed. In the case of the SixTrack slhcv31b powering scheme, the IT magnets are powered like in the Baseline powering scheme, though for the calculation of the normalized strength it is not taken

into account that Q1 and Q3 are in series, and Q2a and Q2b as well, leading to a factor 2 between the Baseline powering scheme and the SixTrack slhcv31b. The yellow line “v31.b SixTrack x10” is the tune shift for SixTrack slhcv31b, but with the complete spectrum amplified by a factor 10. For the v31.b SixTrack x10 and SixTrack slhcv31b no decrease of the DA in respect of the reference case without ripple is observed, while in the case of an amplification of the spectrum by a factor 100 the DA visibly decreases in respect of the reference case. Thus the tolerance for the real spectrum in terms of tune shift must lie between an amplification by a factor of 10 and 100.

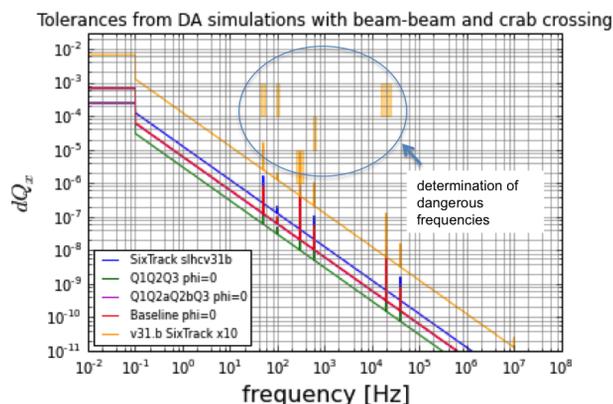


Figure 2: Tolerances from DA simulations expressed in terms of horizontal tune shift. A similar plot is obtained for the vertical plane. The red line of the Baseline powering scheme is superimposed over the pink line for the Q1Q2a-Q2bQ3 powering scheme.

CONCLUSION

The requirements for the powering scheme of the HL-LHC triplet have been determined with Monte Carlo simulations for the low frequency current-control regime and for the high frequency voltage-control regime with DA simulations. In the voltage-control regime the tune shift for the Baseline powering scheme amounts to 1.36×10^{-4} and can be reduced by a factor 2.0 with the Q1Q2Q3 scheme and a factor 2.5 with the Q1Q2a-Q2bQ3 scheme. In the current-control regime the maximum tune shift expected for the different powering schemes lies in all cases below the obtained tolerances. As in the voltage-control regime all frequencies are in phase the tune shift only depends on the circuit inductance and is thus smallest for the Q1Q2Q3 and a factor 2.0 larger for the Q1Q2a-Q2bQ3 and 2.1 for the Baseline scheme. In summary, the Q1Q2Q3 would thus be preferable from a beam dynamics point of view as it features a small maximum tune shift in both regimes.

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